AIAA-2001-1618

DEVELOPMENT OF AN INFLATABLE SAR ENGINEERING MODEL

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Abstract

Deployable and inflatable structures are successfully used in a wide variety of earth-bound applications. Their use in space, however, requires not only assurance that the structure will survive a launch to space, but also certainty that the desired deployed configuration and that the processes of deployment, inflation and rigidization in space will be successful and without posing a threat to the hosting satellite or vessel. For this reason, the manufacture of an engineering model for an inflatable L-Band synthetic aperture radar antenna utilizing rigidizable inflatable structures is critical, prior to a space-based demonstration of this technology. This paper provides a perspective for the design of an inflatable SAR engineering model, an overview of its manufacture, and it reports on the deployment results.

Background

The increasing need for bigger "eyes" from the wide-reaching vantage points of space has opened the way for new programs destined to study the Earth from space. These programs are now benefiting efforts to gather more information on the natural processes on Earth's surface and atmosphere, to understand the mechanisms that govern the existence of ecosystems, their changes, and their mutual interactions. At the same time, the need for larger apertures has motivated the search for ways to make space structures more efficient while capable of satisfying the ever increasing demand for larger antennas, radars, solar collecting areas, and soon, larger vessels for inhabitation, exploration and utilization of space resources.

In response to such demand, for the past several years, the Jet Propulsion Laboratory (JPL) under contract from NASA, has been conducting work in the development of inflatable and in-space rigidizable structures (lately classified under Gossamer Structures). As part of that work, one of the efforts that has fueled investigations and developments in inflatable and rigidizable structures, is the production of a space-borne Inflatable Synthetic Aperture Radar (ISAR) [Ref. 1].

The ISAR is an L-Band (1.25 GHz), membrane-based antenna with dual polarization (Horizontal and Vertical) capability with approximate aperture of 30 m^2. The primary goals of the ISAR project are: to demonstrate the readiness of inflatable-rigidizable structures as a viable solution to the challenges that high structural weight poses on current space-based synthetic aperture radars (SARs), to verify on-orbit contolled inflation deployment, planarity and separation of large stretched membranes, and space rigidization of inflatable tubes or beams.

An ISAR space demonstration on Space Shuttle or International Space Station facilities is now envisioned, as a means to achieve the goals mentioned above. Figure 1 shows the ISAR as it would be configured after deployment from the Mission Peculiar Experiment Support Structures (MPESS) palette during a Shuttle flight demonstration.

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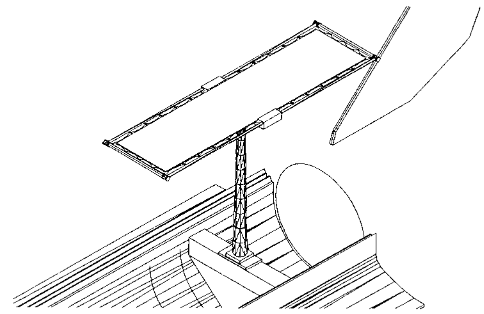

Fig. 1- Drawing of Deployed ISAR

The antenna would interface with the MPESS through a telescopic-deployable mast. At the top of the mast, there is torque box from which the two antenna wings are cantilevered; each wing is supported by a pair of inflatable-rigidizable tubes which are interconnected by a rigid cross-member at their free-ends, this forms a frame which provides structural support for the antenna membranes.

While there is no flight yet manifested for such a demonstration, current work focuses to advance the efficiency, reliability, and space compatibility of the various components of the ISAR design, as well as its overall readiness for a demonstration flight.

The most recent, major task conducted, is the development of an engineering model (EM). The main objectives for the EM is to prove that tube inflation, antenna membrane deployment, and rigidization will take place in the predicted manner, which, upon sucessful completion, provides validation for the ISAR baseline design. This implies the assumption that the dynamics of deployment and rigidization are similar on the ground to those anticipated in space; in fact, ground deployments of large, lightweight structures like the ISAR, are widely known for ground deployments that are far more challenging and difficult to attain than in the micro-gravity environment of orbital space.

Engineering Model Design

The EM has the exact configuration as the intended space-borne design and contains the same components and design parameters. For practical reasons however, some materials have been substituted.

The ISAR antenna design has a rectangular shape, with length of 31.2 ft (9.5 m) and width of 9.7 ft (3.0 m); the antenna is comprised of two identical but structurally independent wings. The EM, however, features a single wing design, as seen in Fig. 2.

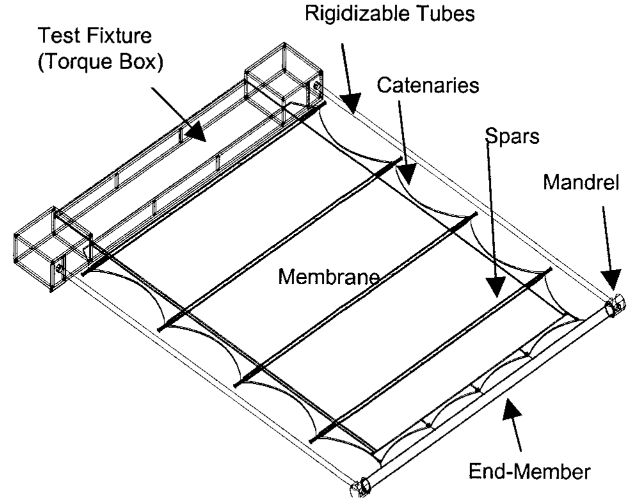

Fig. 2 - Schematic of ISAR Engineering Model

The main component groups of the antenna design are: The membranes, a pair of inflatable/rigidizable tubes or booms, the tensioning system, and the test fixture.

The Membranes. The antenna design features three (3) Kapton^{TM} membranes as the support for the RF components. The top membrane contains all the radiating patches, the middle membrane is the ground plane, and the bottom membrane contains the power dividing transmission lines. Each membrane uses 2-mil thick Kapton^{TM}, the patches and transmission lines are made of 5 micro-meter thick copper traces over the Kapton. The patch and transmission line designs are rendered through an etching process that removes the extraneous copper and leaving only the copper that defines the intended design.

As shown in Figure 3, which provides a schematic of the patch membrane and its various elements, each membrane is formed by a set of eight identical parallel strips. In the case of the patch membrane, each strip is patterned with four pairs of parallel patches along the membrane length. Except for power distribution and RF power connector through-hole patterns, the ground plane strips have no patterns, so it features a continuous copper-clad Kapton^{TM}. The power-divider membrane features eight pairs of parallel networks, each of these networks divides and distributes power to one row of radiading patch subarrays.

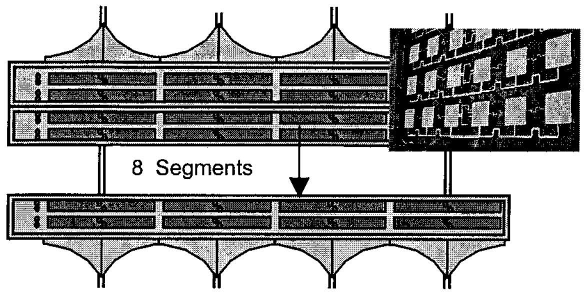

Fig. 3 - Schematic of Patch Membrane (w/Patch Subarray)

Each membrane plane is built by carefully taping each of the eight strip segments to each other, in a way such that all connector holes are alligned accross membrane planes. Kapton™ tape of quarter-inch width and 0.002 inch thickness was used to adhere the membrane strips.

A careful and meticulous process was followed in the entire membrane integration. To avoid difficulties associated with static electricity, commonplace in handling Kapton™, a vacuum table was build. The vacuum table helped maintain any two adjacent membrane strips adhered to the suctioning surface of the table while maintaining mutual allignment while the adhesive tape was applied. Also, as shown in Fig. 4, a set of two mandrels was used to feed and take-up the membrane strips in the taping process.

Fig. 4- Patch Membrane Integration

To facilitate membrane adhesion and integration, allignment marks were designed along with the patch, line and ground plane membrane designs.

Transmission of energy from the power-distribution membrane to the radiating patches is done with brass pin-connectors (See Fig. 5). At their ends, these connectors are soldered to the copper surface on the patch and the power-distribution membranes. Hole patterns are etched each membrane marking the location where the through-holes are to be punched, and holes are drilled on the spars to accommodate the connectors.

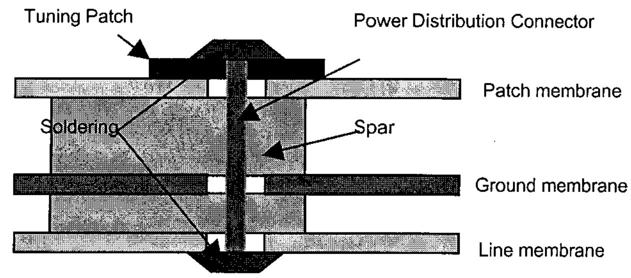

Fig. 5- Schematic of Power Distribution Connection

After each membrane plane was completed, a series of membranes with catenary-shaped boundaries were attached to the periphery of each membrane plane. The catenary membranes are the interface between each membrane plane and the tensioning system. The catenaries use 0.005 in. thick Kapton™ as the interface between the tension lines and the antenna membranes.

After integration of the catenaries to the membranes, each of the membrane planes is then ready for integration to the test fixture or torque box, and to the tensioning system.

Tensioning System. The tensioning system is comprised of a set of four spars, the catenaries around the periphery of each of the membranes, and the end-member (See Fig. 6). Three springs at each spar-end enable balancing of tension loads between adjacent catenary spans. In the deployment process, tensioning of the membranes is achieved by rigidization of the inflatable tubes, this produces tensile loads on the catenary lines, through the end-member and spar interfaces; this loads the catenary membranes, which in turn produces the desired antenna membrane in-plane stress.

In order to obtain the specified membrane plane spacing and plannarity, each of the membranes requires a bi-directional in-plane stress of approximately 50 psi. The in-plane stress is achieved through the use of catenaries along the periphery of each of the membranes. The catenary tension is achieved through springs interfacing with the end-member. Therefore, the membrane mechanical interfaces and the spars are responsible for dictating and maintaining both separation and membrane plannarity.

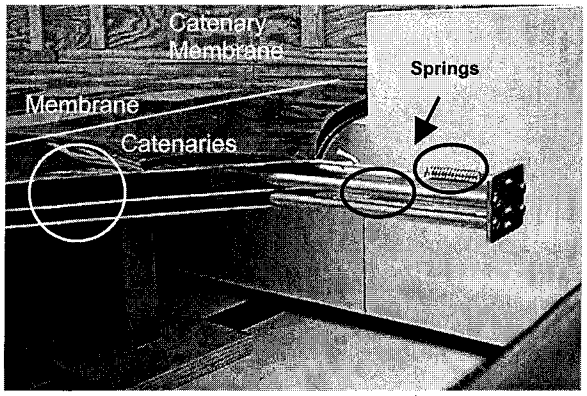

Fig. 6- Membrane Tensioning System

The required separation between the patch membrane and the ground is 0.5 inches (1.27 cm) and between the ground plane and the power distribution membrane is 0.25 in. (0.635 cm). The membrane plannarity is characterized only in qualitative terms as the best membrane flatness that will provide acceptable performance, it does not take a lot of effort to obtain acceptable plannarity for this membrane-based L-band antenna.

In order to load catenaries that are parallel to the inflatable tubes, each converging catenary line must have a tension load of 3.8 lbs at the apex of the catenary; this causes a total compressive load of 14 lbs on each spar (all three membranes combined) and provides a transversal stress field of 50 psi on each membrane. The catenaries parallel to the end-member load the membranes with a longitudinal stress field of 50psi. All catenary loads are transfered to the end-member, and may be resolved into compressive and lateral loads as shown in Fig. 7.

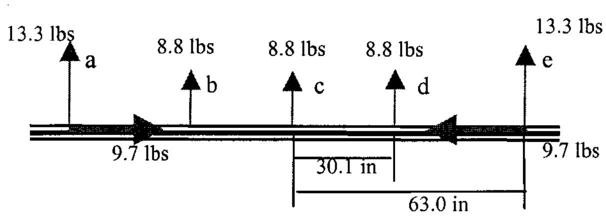

Fig. 7 – End-Member Force Diagram

The combined lateral loads are ultimately reacted by the inflatable tubes, putting each tube under a compressive axial load of 26.5 lbs.

The interface between the end-member and the catenary system is through a set of three springs (one per membrane plane), at each of the interface locations (**a**, **b**, **c**, **d**, and **e** in Fig 7). These interfaces are shown in the two views of Fig. 8. A coil that attached to the end-member through a rope wrap, supports the three interface springs.

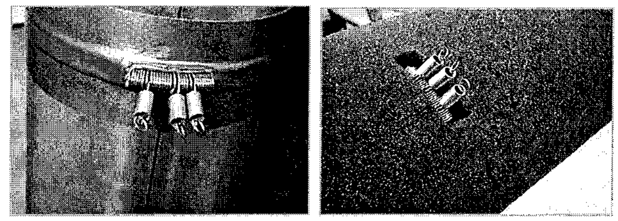

Fig. 8- End-Member/Catenary Interfaces

Development of Catenary Profiles. The EM uses a system of catenary lines and membranes to stretch the antenna membranes to the desired in-plane stress of 50psi.

There is only a few variables in the mathematical definition of the catenary profile, most of which are readily defined or constrained by design requirements or choices. The form of the equation varies depending on geometric loading; in this application, the load is constant and linearly distributed along a horizontal with respect to the catenary lines; this is also the case of a suspended flat bridge.

So, the catenary load relations are ruled by the quadratic equation (a parabolic catenary profile), as shown in Fig. 9.

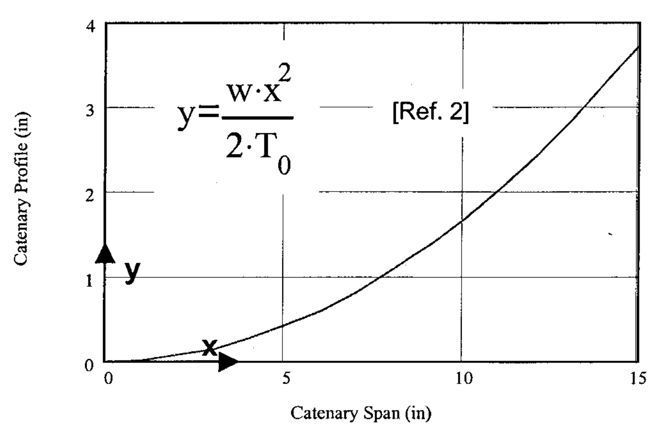

Fig 9 – Catenary Profile

Where **w** is the constant linear load, **x** is the span-wise displacement, and $\mathbf{T_o}$ is the constant horizontal component of the catenary load.

In this application, the choice of catenary profile is driven by the dimensional constraints and membrane stress. The constant linear load **w** may be expressed as the product of the membrane stress (σ) and its thickness (**t**), the span length **L** between two catenary support points is introduced instead of **x**, and **y** is replaced with the catenary depth (**d**). Therefore, the load equation is given as,

$$T_o = \frac{\sigma \cdot t \cdot L^2}{2 \cdot d}$$

Since both the stress and the membrane thickness are known, there are choices regarding catenary span length and depth. Our design however, constrains the horizontal catenary spans because of our desire to place the spars (catenary supports) at the location of the power distribution connectors (for support when soldering and membrane separation); though, this is not the case for the vertical catenaries.

Another important consideration in the choice of catenary parameter values, was the interface of the horizontal and vertical catenary systems to the end-member. Common interfaces between the horizontal and vertical catenaries with the end-member were chosen at the corners, thus minimizing interface points. Fig. 10, shows the force diagram illustrating the mechanical interaction between the catenary corners and the end-member.

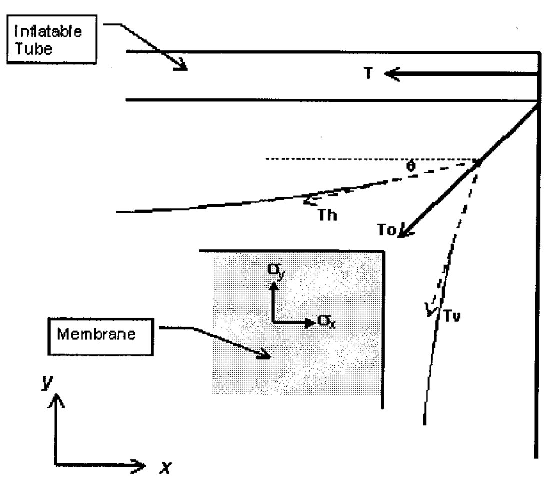

Fig 10 – Catenary Forces at End-Member

A parametric study was conducted to choose the appropriate catenary profiles for our design (See Fig. 11).

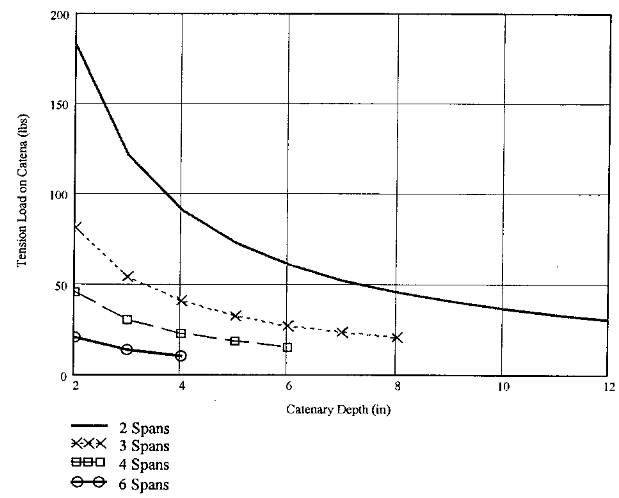

Fig 11 – Catenary Span Parametrics

It is easily appreciated that catenary loads decrease with increasing number of spans, and with greater catenary depth. In order to minimize loads on the structure, a greater number of catenary spans and large depth would be desirable. But, as mentioned earlier, the number of spans in the horizontal membranes is constrained by the four spars, and very deep catenaries would increase the design size. Therefore, a profile of relatively low catenary tension and moderate depth was chosen, such that $\mathbf{T_o}$ is 3.0 lbs and depth **d** is 9.1 inches for the horizontal catenaries and 3.75 inches for the vertical ones. Note that both horizontal and vertical catenaries have the same profile, their depths vary because the spans are different.

This catenary profile produces a net axial compressive load of 26.5 lbs on each of the inflatable tubes. Fig. 13 shows the respective force diagram.

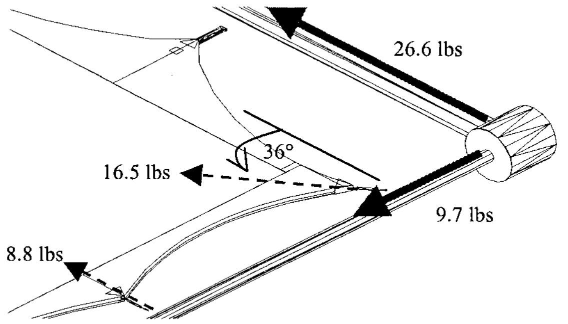

Fig. 12 – Catenary Force Diagram at Tube Interface

Inflatable/Rigidizable Tubes. The inflatable and rigidizable tubes have the function of actuating the deployment and providing structural support once full deployment is achieved. They span the length of one antenna wing and have a tubular design with reinforced walls made of a thin aluminum laminate. They weigh in at 0.12 lb per linear foot; in the present design, each tubes weighs 1.9 lbs.

The inflatable/rigidizable tubes allow rolling of this SAR antenna and its support structure into a relatively compact configuration. They stow flattened and rolled up around the mandrels. During deployment, the tubes are slowly inflated, which causes them to unroll from the mandrels; as the internal pressure increases, the tubes slowly adopt their nominal cylindrical shape.

The tubes are cantilevered from the test fixture and joined at the other extreme by the end-member, forming a frame around the membranes, which defines one of the two full-antenna wings.

The tubes must be capable of sustaining a compressive load of 26.5 lbs without buckling. Qualification load tests showed the tube current design capable of sustaining an axial static load of 134 lbs, which establishes a minimum load margin of 5. Current mission requires a margin of 1.25.

Fig. 13 provides a schematic of the tube design when in deployed configuration. Each tube is made of a circular cross-section of 3.0 inch- diameter, wall thickness of approximately 0.005 inches, and length, including end-caps, of 15 feet and 7.85 inches.

The tube walls are a composite with an aluminum sheet of 0.003 inches sandwiched between two films of polyester, each of approximately 0.001 inches in thickness. The tubes are reinforced with four steel ribs that run the entire length of the tube; the ribs have a semi-circular cross-section with thickness of 0.0064 inches and are placed every 90 degrees around the circumference of the tube cross-section; the ribs are purchased off-the-shelf as carpenter tape replacement blades (Sears™ brand Catalog No. 39181); this option is not only inexpensive and convenient, but also qualified for space use and has already flown in many satellite missions.

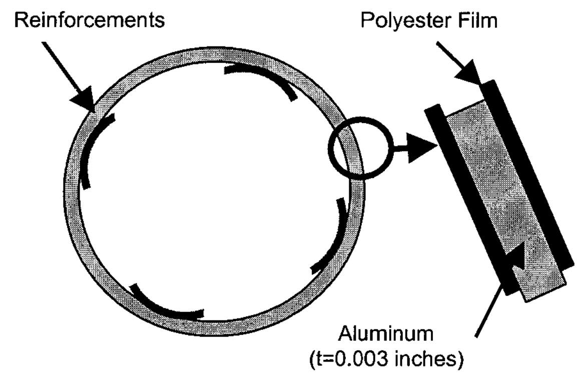

Fig. 13 – Schematic of Tube Cross-Section

Using the rib reinforcements not only provides significant stiffness to the tubes but also assures Euler buckling behavior. Without this reinforcement, tube buckling would be largely dominated by local deformations.

As may be appreciated in Fig. 14, construction of the tubes is accomplished by seaming the aluminum composite sheet into a closed surface. The seam is reinforced with adhesive tape on both sides of the tube. The wall material and the rib reinforcements should be continuous pieces of material along the tube length, to avoid stiffness discontinuities across any splicing.

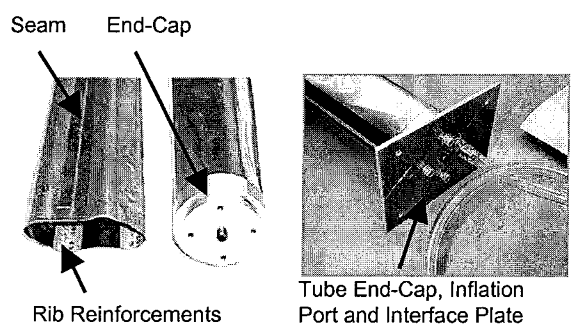

Fig. 14 – Inflatable/Rigidizable Tube

A pair of end-caps per tube is used, which seal the tubes and also provide interfaces with adjacent components (mandrels and test fixture). The endcap interface to the test fixture also features a port for tube inflation as shown in Fig. 14.

The Rigid End-Member. The end-member is a simple, yet very important element in the ISAR-ME design. It is made of a round cylindrical tube of aluminum, with wall thickness of 0.0625 inches, length of 12 feet 5.69 inches, the tube outer radius is 5.0 inches. Analysis shows that a wall thickness of 0.03 inches gives the end-member a load margin of 5; therefore, the engineering model design has a margin above 10.

When the antenna is stowed, the end-member acts as a mandrel around which the membrane array, the catenaries and the spars are wrapped. During deployment, the entire bundle rotates unfurling the antenna. After deployment is complete, the end-member reacts all the catenary loads, and through the mandrels, transfers axial loads to each of the tubes (as shown in Fig. 13).

A foam cover is used on the end-member to provide a consistent and soft surface for the membranes to roll onto, when the antenna is in stowed position.

Mandrels. The mandrels are each located at the extremes of the end-member; their primary function is to serve as spooling devices for the tubes around which they are stowed. They also serve as an interface between the end-member and the tubes.

The mandrels are basically short, thin walled, hollow cylinders, with ports and interfaces for the tubes and the end-member. Fig. 15 shows a diagram and a picture of a single mandrel.

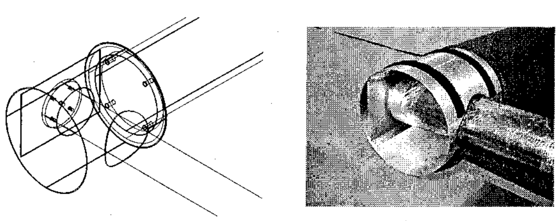

Fig. 15 – Mandrel Design

Spars. The spars are a set of four rigid member pairs placed at discrete locations in the mid-span area of the antenna membranes. Each pair is comprised of two nearly identical beams, only differing in thickness, and rigidly attached to each other by plastic screws; they are composite beams, manufactured with Nomex honeycomb and fiberglass facesheets. A tension bracket that interfaces with the catenary system is provided at each spar-end (See Fig. 16).

In addition to providing mid-span spacing for the membrane planes, the spars are structural members taking compression loads from opposite sides of each antenna membrane. Since they are located between radiating membrane planes, the

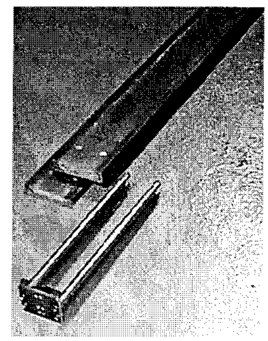

Fig. 16 – Spar with Tension Bracket

spars are required to have a very low dialectric constant; the use of fiber glass facesheets and nomex honeycomb has proven to be adequate in previous RF tests.

Test Fixture. The engineering model test fixture is actually a wooden mock-up of the torque box intended to interface the entire ISAR antenna to a supporting bus or structure. As in the case of the torque box, the test fixture provides reaction to all loads generated by the antenna wing. The rigidized tubes are cantilevered from the fixture, and in conjuction with the tubes and the end-member, it forms part of the rigid support frame for the antenna wing (See Fig. 17).

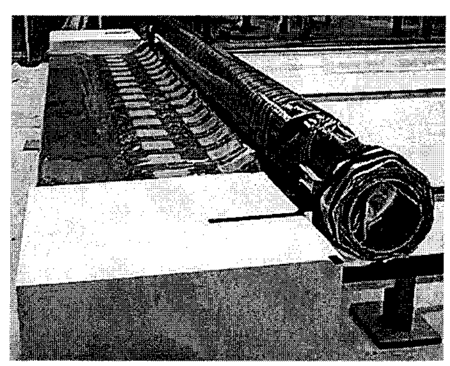

Fig. 17 – Test Fixture with Rolled Antenna Wing

In this engineering model, the antenna membranes are attached to the test fixture through a set of two flat composite boards; these boards also separate the patch, ground, and transmission line membranes from each other. Since the RF power connectors are located transversally at the center of the antenna design, the boards provide installation and access ports, as shown in Fig. 18.

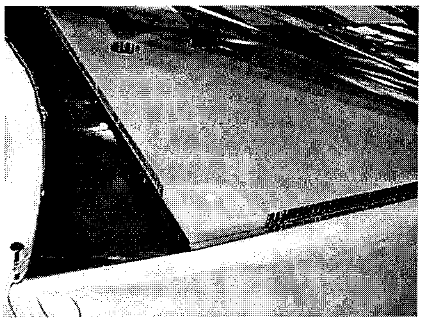

Fig. 18 – Composite Boards

The boards are made of 0.031 in. thick fiberglass facesheets with nomex honeycomb sandwich. Similar to the spars, the boards have overall thickness of 0.50 and 0.25 in, which is the required membrane saparations, and have a very low dialectric constant.

Depending on the design of the torque box, reinforcement with capped edges and mid-span stiffners may be required in a flight design of these boards.

Engineering Model Weight. The total weight of the EM is 146 lbs (66.2 Kg), it includes all components except the gas (air) supply for inflation, which was part of the installations at the deployment site. This weight reflects the substitution of materials in some parts, such as the test fixture (torque box), end-member, mandrels, tube end-caps, and spar stand-offs, instead of carbon composite materials intended in a flight article.

Calculations indicate that the use of carbon composites instead of aluminum or other materials, wherever possible in a flight article, would result in a total mass of 52 Kg for the entire antenna (both wings). This results in an aerial density of 1.6 Kg/m^2 of antenna aperture; it does not include the transmit-receive (TR) modules (~10Kg), antenna electronics equipment (~10Kg) and cable harnessing (~7 Kg).

Mechanical Deployment

Deployment test of the ISAR mechanical engineering model was performed in mid September of 2000. This followed a series of trial deployments which provided valuable information regarding membrane and tube stowage and deployment behavior. The deployment sequence may be appreciated in the pictures presented in Fig. 19.

Deployment speed is a function of air flow rate; the nominal deployment rate chosen for the engineering model demonstration was that obtained from applying an air supply of 1.5 psi to the inflation system, the entire deployment took about 7 minutes (this is equivalent to an approximate air flow rate of 5 gm/s).

Motivated by schedule and funding constraints, a horizontal deployment configuration was chosen for deployment test demonstrations. However, a vertical deployment with gravity-offset mechanisms is desirable, which would display a nearly weighless membrane effect in the deployment process and membrane flatness. Deployment simulations would also be easier to correlate.

In the deployments conducted, it was observed that the individual tubes inflated at the same rate, such that the end-member always remained parallel to the test fixture throughout the process. Although the membranes appeared relaxed as they unrolled from the end-member, they immediately stretched to their desirable "flat" profile (membrane and spar bending were actually noticeable due to gravity effects) once the tubes reached their fully extended configuration and began increasing their internal pressure.

The tubes took an additional time of approximately 1 minute to overcome local buckling on the reinforcements near the mandrels and the test fixture. Full recovery of the tube cylindrical shape, with no rib-failure was attained every time, this provides certainty that the tubes recovered their fuctional stiffness.

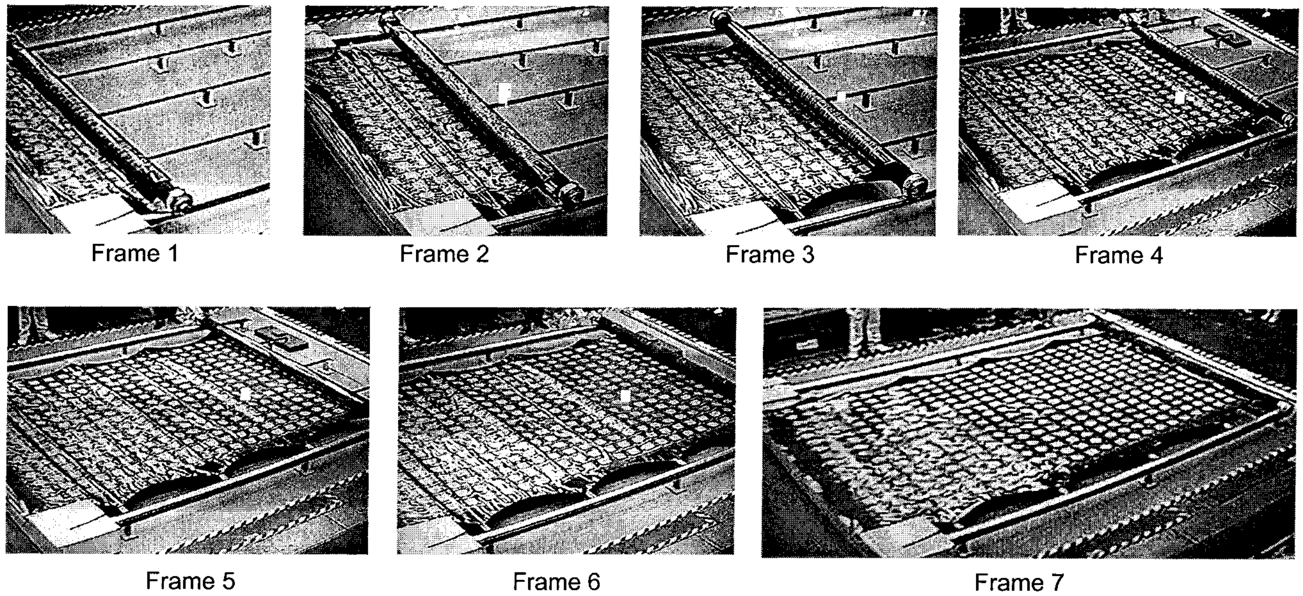

Fig. 19 – Antenna Deployment Sequence

Conclusions

In our deployment demonstrations, flawless and controlled inflation, consistent membrane separation and overall plannarity, and rigidization of the supporting tubes to their designed stiffness levels were all successfully achieved.

In the process of completion of the ISAR engineering model, integration of its various design components, the successful deployment of the antenna membranes, and inflation of the tubes followed by their rigidization, demonstrate that the current mechanical design of the ISAR, using inflatable/rigidizable tubes for actuation of antenna deployment and rigid support, is sufficiently ready for design efforts conducive to a space-borne demonstration of these technologies.

Future Work

While integration of the EM components and the deployment were successful, work in the areas of thermal characterization of the structures, elimination of risks by tube wall micro-cracks, design optimization, performance requirements of adhesives and space qualification for a variety of materials, remain as areas open for future work.

Acknowledgements

The authors wish to thank Dr. Lih-Min Hsia of California State University, Los Angeles, and his team of students for the successful manufacture of the inflatable/rigidizable tubes, end-caps and mandrels; to Tamer Elsayed of California State Polytechnic University, Pomona and Justin Abruso of University of California, Santa Barbara for their support in the integrantion process.

This work was performed at JPL, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA)

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